OPTIMAL DESIGN OF HEAT RECOVERY SYSTEM

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ABSTRACT

High energy usage has been a huge problem in all areas of the chemical industry. With the growing awareness of green engineering, energy usage needs to be reduced by some means. This study explains how energy usage is reduced through atechnique called process integration which is achieved through mathematical programming. Software called Generalized Algebraic Modeling System (GAMS) is used to do the mathematical programming. Although many methods can be used, this paper covers the usage of Linear Programming (LP) to reduce energy usage. An ethylbenzene plant in Korea was used as a case study (Yoon et al., 2007) to verify the model developed. Transportation model was used as the mathematical model to solve this problem. The procedures involved 3 steps, (1) data extraction from the process data, (2) superstructure representation, and (3) mathematical modeling. The simulation results produced by GAMS were analysed based on three important criteria to select the valid match ups between hot streams and cold streams. As a result, usage of cooling and heating utility was reduced by 79.3% and 28.2% respectively.

REKA BENTUK OPTIMUM SISTEM PEMULIHAN HABA

ABSTRAK

Penggunaan tenaga yang terus menerus meningkat telah menjadi satu masalah yang besar dalam semua bidang industri kimia. Hal ini kerana sumber tenaga seperti bahan bakar semakin berkurangan. Oleh itu, beberapa pendekatan digunakan untuk mengurangkan masalah ini. Sehubungan itu, kajian ini menerangkan bagaimana penggunaan tenaga dikurangkan melalui integrasi aliran proses yang dicapai melalui pengaturcaraan matematik. Perisian yang dipanggil Pemodelan Umum Sistem Algebra (PUSA) digunakan untuk melakukan pengaturcaraan matematik. Walaupun banyak kaedah boleh digunakan, kertas ini meliputi penggunaan Pengaturcaraan Linear (LP) untuk mengurangkan penggunaan tenaga. Sebuah kilang ethylbenzene di Korea telah digunakan sebagai kajian kes (Yoon et al., 2007) untuk mengesahkan kebolehan sistem ini. Model pengangkutan telah digunakan sebagai model matematik untuk menyelesaikan masalah ini. Prosedur yang terlibat 3 langkah, (1) pengekstrakan data dari data proses, (2) mahastruktur perwakilan, dan (3) pemodelan matematik. Keputusan simulasi yang dihasilkan oleh PUSA dianalisis berdasarkan tiga kriteria penting untuk memilih integrasi sah antara aliran panas dan sungai sejuk. Hasilnya, penggunaan penyejukan dan utiliti pemanasan telah dikurangkan sebanyak 79.3% dan 28.2%.

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LIST OF SYMBOLS / ABBREVIATIONS

cp	specific heat capacity, J/(kg□K)
F	flowrate, kg/hr
Hn	hot stream number
Cn	cold stream number
Xn	amount of heat energy that will be shared by two streams, kW
Z	total heat duty / total enthalpy, kW
ΔH	enthalpy / heat duty, kW
Tin	inlet temperature, °C
Tout	outlet temperature, °C
ΔT	temperature difference, °C

GAMS	general algebraic modelling system
HEN	heat exchanger network
HENS	heat exchanger network synthesis
LP	linear programming
MILP	mixed integer linear programming
MINLP	mixed integer non linear programming
NLP	non linear programming

CHAPTER 1

INTRODUCTION

1.1 Research Background

Energy demand is increasing as a consequence of population growth and economic development. Economists will consider on profit, trading, and market of energy when they give definition on it. It is differ with socialists and humanists; they are talk lots about the future energy needs for living life being. The politicians look energy as could be manipulated in order to maintain their power either by using military and government that they care off. Even though, the fact that energy productive sources continue to decrease which correspond to less renew energy cannot be denied. This make the energy conservation remains the prime concern for many organizations, authority, and private institution especially in process industries. In December, the U.S. Energy Information Administration released a sneak preview of the 2011 outlook report. The consumption numbers is expressed in graphical form because it is most effectively portrayed that way. Figure 1.1 shows that industries lead the consumption of energy and the detail for componwnt in industies is illustrated in Figure 1.2.

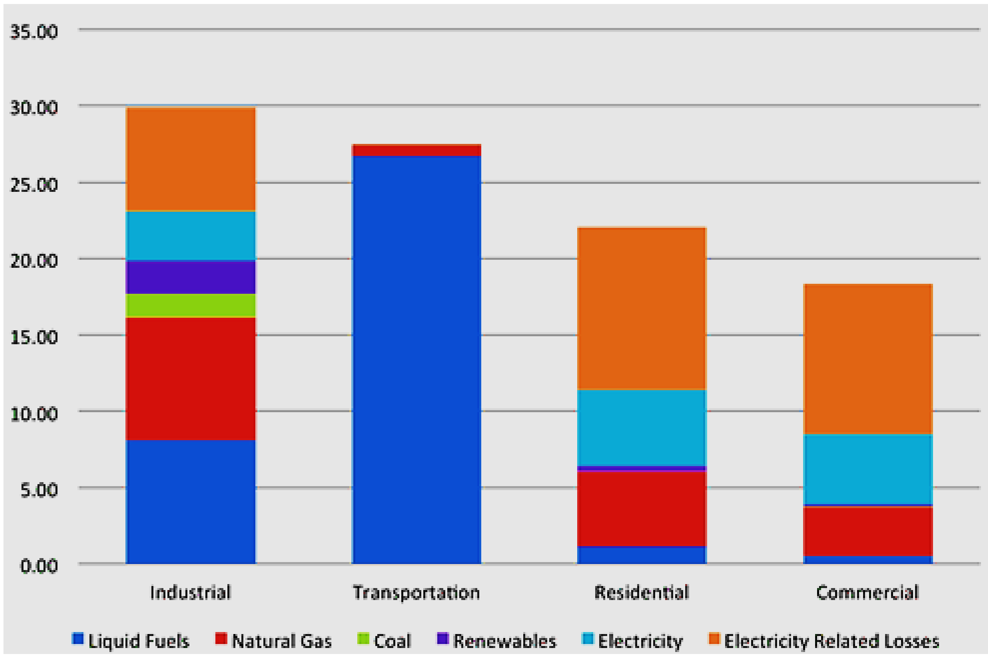

Figure 1.1 Energy Consumption (BTU) by Sector. (Source: Annual Energy Outlook Consumption 2010)

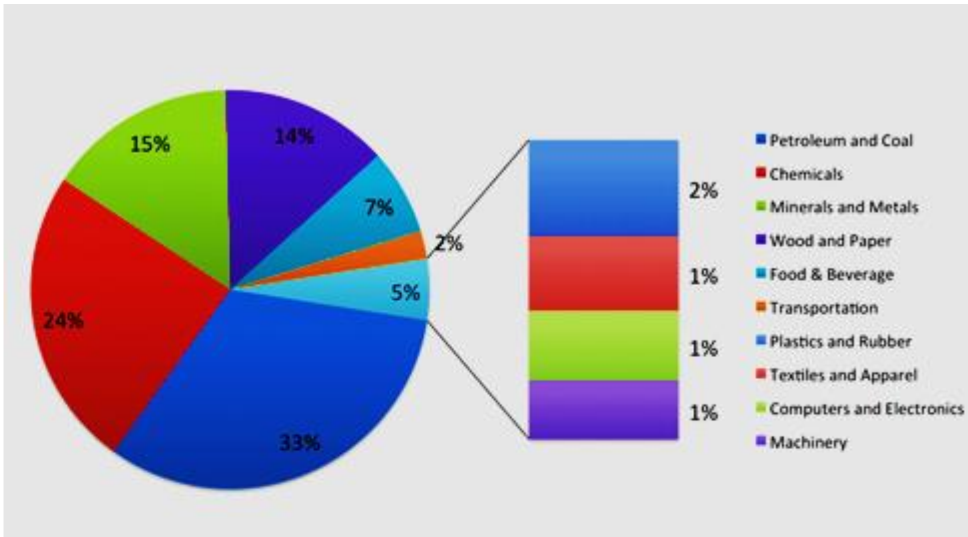

Figure 1.2 Industrial Energy Used with Proportion by Industry. (Source: Annual Energy Outlook Consumption 2010)

Since industry sector leads the consumption of energy, the purpose of energy savings, the methods of analysis, synthesis and optimization are becoming more important. Some challenges must be face and overcome such to optimize energy consumption with industrial rapid growth. Sometimes, the step to achieve this purpose will deplete lots of money after considering capital investment, operational costs related to friction losses, and maintenance costs deriving from the cleaning schedule (Antone *et al*,. 2011). Lizbeth *et al*. (2010) have been proved in their work which is minimizing costs and optimal energy savings could be achieved simultaneously. Heat integration become the famous focussed activity in industry or process plant in term of the development of optimal design system. The optimal design could be done by fixed the objective function as to maximize heat recovery.

Heat exchanger become a very useful equipment but it is not effective if it just to function without any adjustment. Kesler and Parker (1969) have noticed about this thing started long time ago and they decided to divide each stream into small heat duty elements of equal size and posed the matching between hot and cold elements as an assignment problem. The reseach has been improved and has many new tecnology researches on it until this thesis was written with introduce the mathematical modelling development. The common topic about heat exchanger network (HEN) was included a set hot streams that need to be cooled at the inlet temperature to the outlet temperature, a set cold streams that need to be heated at the inlet temperature to the outlet temperature, the heat capacities and flow rate of the all streams, the utilities available, and heat exchanger costs.

1.2 Problem Statement

Energy sources are kee decreasing which is corresponding to the growth of energy consumption and demand. It was getting more complicated because of the limited alternatives for unrenewable energy sources. It was giving impact to the cost of the energy in market that doing energy businesses. At the same time, industrial sectors have very instant energy consumption which needs to be optimized. Optimization of heat integration was really help in reduce the cost that spent for large number of heat exchangers, utility used and other related variables. Thus, the reduction of heat consumption can be done by maximizing heat recovery through development of mathematical modelling.

1.3 Objective of the Study

The objective of this study is to develop a mathematical approach for designing and formulate a system in order to achieve the optimum heat recovery.

1.4 Scope of the Study

There are three research scopes for this work which are:

i) To analysis techniques related to energy reduction.
ii) To develop mathematical formulation for optimal design of maximum heat recovery.
iii) To applied for optimization model on industrial case study in order to illustrate the effectiveness of the proposed approach.

1.5 Significant of Study

This study is very important in order to determine the optimal design of heat recovery which corresponds to minimize utility consumption.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter summarizes all the selected researches and works that have been done by previous researchers. A general review on heat exchanger network, using pinch analysis and mathematical programming are discussed in Section 2.1. The explanation about these two methods is focused on current and previous works. Several other methods also be introduced and the last is problem and selection.

2.2 Heat Exchanger Network

Heat exchanger network (HEN) synthesis is a study on how to develop network either integration of utilities or process streams in process engineering systems which can affect the energy recovery and energy costs. The common subjects that are discussed in HEN designation are set of hot process streams to be cooled from the inlet temperatures to the outlet temperatures, set of cold process streams to be heated from the inlet temperatures to the outlet temperatures, the heat capacities and flow rates of the hot and cold process streams, the utilities available and the temperatures or temperature ranges and the costs for these utilities, and heat-exchanger cost data. Historically, Broeck (1994) had proposed this kind of design basic problem and before that Hwa (1965) take more seriuos to extend the research till the grassroots. Masso & Rudd (1969) took initiatives progrresively manage the basic problems using algorithm methode involving often some established optimization principles. Extensively, Shenoy (1995) and Smith (1995) have been proposed the fundamental of HEN systematically.

2.3 The relation of Energy Recovery and Energy Cost

Heat exchanger network synthesis (HENS) problems have the significant priority to be solved. It is because lots of energy can be saved and be used back. As correspond to the energy costs increament, industries have greater incentive to apply heat integration as broadly as possible in its facilities (Errico, 2006). In practice, industrial plants are usually cold process streams that need heating and hot process streams that need cooling, usually achieved using hot and cold utilities and consequently increasing energy costs. One way to reduce these costs is by matching and configuring the process streams, which is the hot process streams would be match with cold stream process streams, with all possible routes and with certain constraints. In order to reduce the energy costs to a minimum, the most effective exchange of energy between process streams must be obtained. The trade-off between energy recovery and energy costs involved really complex design of solution. Conventional methods do not, however, accurately capture the three-way trade-off between heat exchanger units, heat exchange area and energy used (Sethna et al., 2000). Besides, utilities also are one of the important factors that affect the trade-off.

The most widely used utilities belong to three different types which are hot utility, including steam, coal, hydrocarbon fuels; the cold utility including cooling water, and air; and work utility, which transports process loads within the system, with the simultaneous generation or consumption which is electricity and shaft work. Each utility has an associated unit cost (Konstantinos & Vasilios, 2002). As far as the objective function is considered, Capturo et la., 2008 make conclusion there are most authors consider the sum of capital investment related to the heat transfer area, and energy related costs. In order to get the optimum solution and to overcome the complexity, pinch analysis techniques and mathemathical modelling become famous widely used method and always continuously improved from day to day. Pinch analysis was presented (Linhoff, 1979), and mathematical modelling was proposed (Weaterberg & Grossmann, 1985).

2.3.1 Pinch Analysis Technique

In this technique, hot and cold streams are match to get the maximum energy recovery (MER) network. The search space of possible design solution can be reduced. The essential matches, matching option, and the requirement of streams splitting are decided by certain feasibility criteria. The criterion that needs to be concerned too is the number of streams in the pinch. This implies that to bring the hot streams to their pinch temperature with the cold streams helps. The next criterion is about the temperature in the pinch point. As the temperature is minimum in the pinch, the temperature driving pinch cannot decrease as one move further away from the pinch. Hot and cold streams must almost just present one segmented straight line in T-Q graph. Linnhoff and Hindmarh (1983) have been explained detail in their research about rule of using this technique. Now, the fundamental principles about this technique have been solved for the past several decades and the research now will not in the pinch technology itself, but with the integration with the other technology or solution such meta-heuristic method (Mofid et al., 2011). However, the pure works on pinch technology will be explained in the next subtopic. It will include the important concepts, targets, synthesis methods, optimization, and flexibility.

2.3.1.1 Previous Works on Pinch Analysis Technique

In this subtopic, the explanation is divided into two phases of work, which are year before 2000 and year after. As reminder, the researches for the first phase will present the fundamental and most of their evolutions on pinch techniques have been accomplished. Linnhoff and Hindmarsh (1983) had solved the HENS problems and achieve in most cases of heat integration a nearly optimal solution using pinch analysis. The method was simple enough to be used with manual calculation and by using this method it is possible to find the highest degree of energy recovery with a given number of capital items (Errico et al., 2007). However, it cannot solve many objective functions simultanuosly. As the alternatives and complementary, most of the methods either use mixed integer linear or non-linear formulations or are based on the pinch method.

Mixed integer formulations are capable of providing the global optimal solution to these problems and may ultimately prevail as the method of choice for HENS, but computational effort currently limits their application in the case of large problems. On the other hand, the pinch method is not able to find the global solution but its application is simple and large HENS problems can be solved especially for industrial designer plant. This, for sure introduce some limitation since the trade-offs between the utility consumption, the number of matches, and the minimum investment cost are not take into account appropriately and it may result in HEN designs that are suboptimal networks (Floudas, 1995). The sequential approach stated by him has limitation, caused researches in the late 1980s and early 1990s focused on simultaneous approaches with focus on the synthesis as a single-task problem considering all trade-offs simultaneously (Ciric & Floudas 1991). These approaches are for sure result in more complex models. However, advances in theoretical and algorithmic aspects of optimization have allowed large scale complex model problems to be solved. Figure 2.1 shows the historical panorama of pinch technology approaches over the last decades.

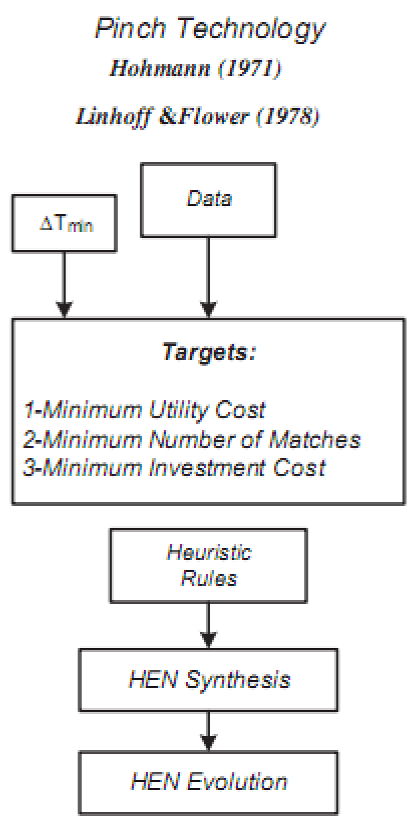

Figure 2.1 Historical panorama of Pinch Technology approaches over the last decades. (Escobar & Trierweiler, 2013)

Through the previous continuous improvement on pinch analysis, Ciric and Floudas, (1990) were obviously explained of their proposal using three temperature approaches with formulate the pseudo-pinch problem for simultaneous network optimization. Approximately one year later, in different paper they came out with the specific simultaneous optimization, included utilities, number of matches, and network configuration. Meanwhile, Jowski (1991) has introduced dual temperature approach (DTA), which is can cause cross-pinching. Even though, this method suitable to be used for stemming from physical insights for HENS. He approved thi work with concern to the PDM, DTA, various HENS targets, and super targeting. In other work, Hui and Ahmad (1994) have been proposed heat integration between different chemical processes in a plant. This is for optimizing the common utility system.

Lee and Yoo (1995) addressed the multiple pinch points with the separation of system which subdivides the HENS problems into independent subsystem with specific one pinch point. Kane and Favrat (1999) have been work on using pinch technology for design HEN for integrated solar combined cycle system. Klemes et al., (1999) have been presented that the pinch method for HENS is applied to an oil-refining plant in the Ukraine which similar to Lababidi et al., (1999) work, but their work was on a retrofit study of an ammonia plant is performed using pinch technology. Pinch technology shows the good progress on solving things regarding to HENS. But, as said by Massimiliano (2007), this method is easy to be utilized, but it is not possible to be sure to achieve the optimal configuration because it is necessary to make heuristic choices. Hossein Y. et al., (2011) still try to defend about the advantage of this method, which is flexible and provides a good view for the designer.

2.3.2 Mathematical Programming

Mathematical Programming Method is very important in order to solve the complex modal. The programming used well known as linear programming(LP), non-linear programming (NLP) mixed integer linear programming (MILP), and mixed integer non linear programming (MINLP) models whereby continuous variables represent process parameters such heat-exchanger duties and stream-split fractions and integer variables represent discrete decisions that is heat-exchanger matches. The applications include methods either with or without decomposition. The problem decomposition is generated by the need to simplify the optimisation. Its most successful version has been proposed in the form of a MILP-NLP approach (Floudas et al., 1986).

The MILP model functions as to determine targets and matches while the NLP is used to optimises the heat transfer areas and the overall cost. If without decomposition, the simultaneous optimisation of matches and heat transfer area are result the complication and make the problem very difficult to solve. Even Viswanathan and Grossmann (1990) said heuristic strategies have been used to try to reduce the effect of non-linear none of the above techniques can guarantee global optimum solutions when solving non-linear MINLP problems. Jelodar et al., (2010) also said the same thing which mathematical formulation of these methods is such that for the bigger networks higher than medium, volume of the optimization problem grows uncontrollably. Figure

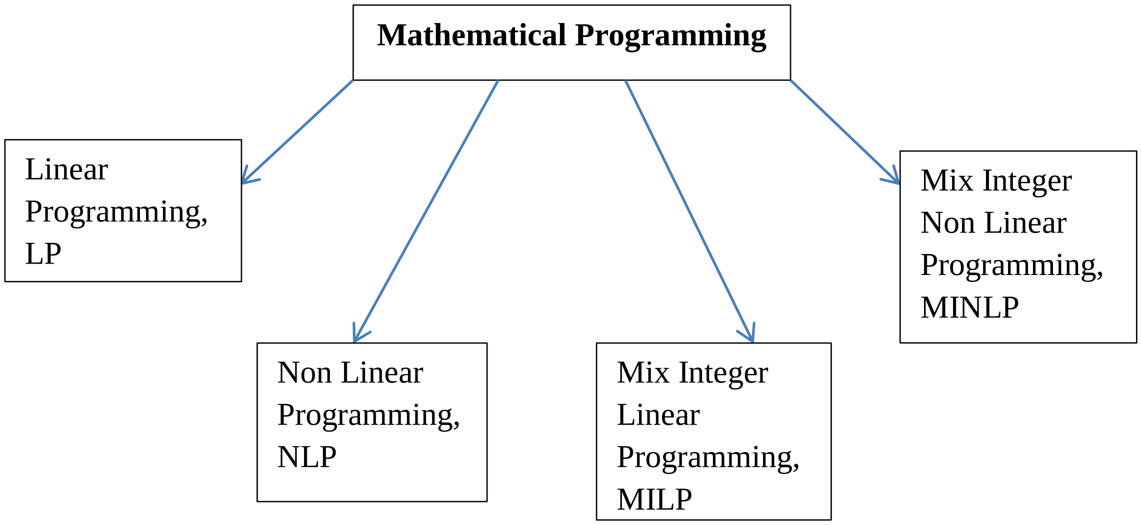

Figure 2.2 Type of Mathematical Programming

2.3.2.1 Previous Works on Mathematical Programming Technique

Papoulias and Grossmann (1983) introduced the linear programming (LP) transshipment for energy targeting. MILP is used by them to formulate the minimum unit problem. Ciric and Floudas (1990) developed an MINLP formulation of the retrofit HENS problem. They solved the formulation using generalized Benders decomposition. In the other work, they discussed retrofit HENS by using an MINLP formulation method that selects process stream matches and match-exchanger assignments while simultaneously optimizing the network structure. This will cause the basis of actual area requirements, as opposed to estimates of area and piping costs.

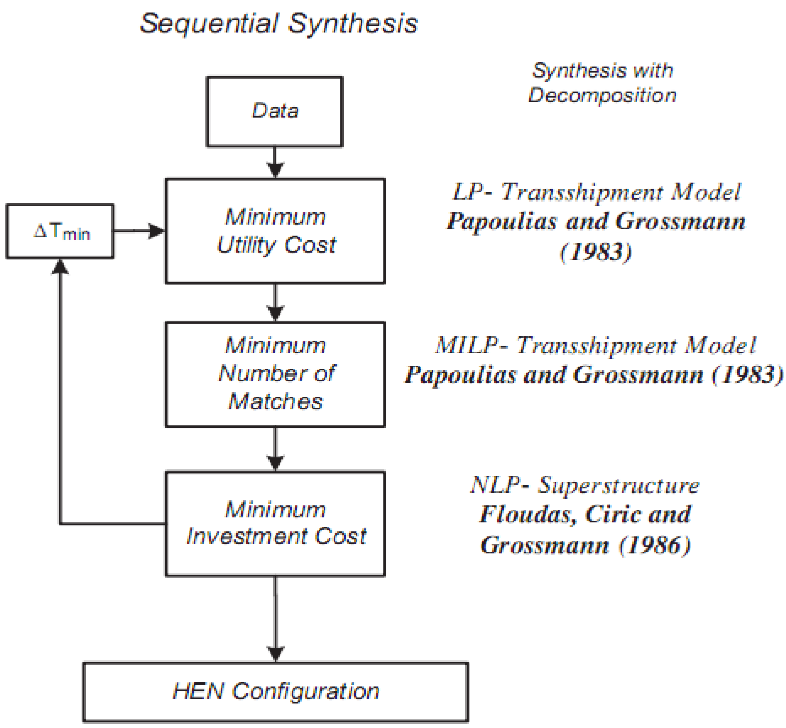

Figure 2.3 Historical panorama of Sequential Synthesis approaches over the last decades. (Escobar & Trierweiler, 2013)

Daichendtand Grossmann (1994) made the effort of Yee and Grossmann (1990) with used in a preliminary screening procedure to determine a subset of solutions from the original superstructure that are bounded to a base-case design. This will reduce the complicated structure of the superstructure. Grossmann and Kravanja, (1995) continue their work on process design and optimization by using MINLP technique. Even this work looks near to completion, Galli and Cerda (1998) have been tried develop three-stage framework for sequential HENS with specified structural conditions involved MILP. It advantage was structural restriction is generalized to allow split networks. An existing HEN is audited for possible modifications, and then these modifications are